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Automated 2D Layout Design of Assembly Line Workstations through Physical Principles

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Abstract

Decreasing product life cycles with increasing product variants force manufacturing companies to adapt their assembly systems to changing conditions. As a result of this, typically manually performed design tasks of assembly workstation layouts often are suboptimal and time extensive. One reason is the identification of complex interactions between resources. This paper presents an approach to support manufacturing engineers in applying physically based modeling techniques to the design process. The model describes relationships between different resources with physical principles. Resources with more impact on the layout are able to obtain their optimum location and influence the locations of other resources.

Keywords: Assembly Workstation Design; Resource Arrangement; Physically Based Modeling

1. Introduction

The design of assembly systems consists roughly of two planning phases [1]. The first phase is the elaboration of the so-called theoretical or conceptual layout of the assembly system. This involves the assignment of resources to processes and the definition of assembly stations – taking into account, among other things, balancing aspects. This initial step is followed by the design of the physical layout of the assembly system. Therefore, decisions are made about the spatial arrangement of workstations and the required conveyor system or transport system in general. The results of the respective planning phases heavily depend on the experience and knowledge of the planners and are very time-consuming when performed manually. For this reason, many approaches exist to automate these planning phases with their sub-tasks [1–4]. However, planning approaches for the automated layout design of assembly systems, in particular of conveyor-connected assembly lines, are underrepresented in the literature. Therefore, within this paper an approach is presented to automatically transform conceptual assembly line layouts into physical ones.

The rest of the paper is structured as follows: The next chapter provides an overview of different approaches to layout planning. Chapter 3 describes the problem formulation, compliance criteria on the approach and assumptions that are made. In chapter 4, the approach is presented in general and in chapter 5, it is concretized by means of an example. Finally, chapter 6 provides a conclusion and future prospects.

2. Related Work

Within this chapter, relevant literature on automated layout planning as well as the used data model for the later presented approach are summarized briefly.

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2.1. Automated layout generation methods

Automated approaches for layout planning exist for different levels of detail. On the highest level, planning methods exist, which arrange departments or machines within the facility. Here, different heuristic approaches are used. An optimizing algorithm called "Harmony Search" is used by Papakostas et al. [5] to arrange and align work centers considering the assignment of human workers. In [6] the authors use a "Genetic Algorithm" in combination with dynamic programming to generate and evaluate layout alternatives for unequal and variable machine/department sizes. A different approach to solve layout issues with unequal-areas is presented in [7]. In this case an algorithm was developed which is based on the heuristic approach of "Particle Swarm Optimization". The arrangement of irregularly-shaped machines with transportation path design is solved in [8] with "Neighborhood Heuristics" and simultaneous use of shortest-path algorithms. Another approach, which considers transportation paths between machines or departments is presented in [9]. The authors formulate the arrangement problem as a "Quadratic Assignment Problem", which is solved using a "Simulated Annealing" heuristic approach. The detailed planning of transportation paths and department orientations is then carried out through a second phase with an "Integer Linear Programming" model.

All aforementioned approaches do not account for possible conveyor-connections between related machines. They also do not consider how resources within their departments or machines are arranged in relation to each other. For this purpose, other automated planning approaches exist, which tackle the cell layout problem.

Most approaches are either restricted to layout planning for robot cells, where the robot is positioned depending on manufacturing machine positions, or machines/supply facilities are positioned depending on the robot [10–13]. An approach to create multi-robot cellular manufacturing systems is presented in [14]. Tasks are allocated simultaneously to the positioning of manufacturing components of the system with a "Multi-objective Genetic Algorithm". But the transport between workstations or robot cells is not taken into account in these planning methods for robot cell design.

One approach, which considers the conveyor transport between workstations is developed by Leiber et al. [15]. The authors present an overall framework for the planning of assembly lines, starting from resource allocation to tasks and finish with the physical arrangement of required resources in the layout. For the layout generation they developed a "Genetic Algorithm" which considers dependencies between resources.

All presented procedures for layout planning are based on algorithms, which rely heavily on randomization. Other approaches found in the literature use physical principles. In [16, 17] the authors are using "Newton's law of motion" and "Newton's law of gravity" to arrange resources for construction site planning in a dynamic context or describe relationships between organizational units in hospital planning, respectively. Another method to model relationships between planning objects is presented in [18, 19]. The authors model departments as point-masses and define relationships as spring-damper-connections.

The big advantage of modeling relations using physical principles lies within the circumstance, that changes in the system do not happen randomly. Objects always move to related objects in order to reach an equilibrium state with the lowest potential energy level.

For this reason, the authors of this paper will present an approach, which utilizes physical principles to generate manufacturing layouts for assembly lines, which considers the detailed layout of workstations and their consisting resources as well as the connection of workstations via conveyor.

2.2. Information modeling: PPR-Model

Information models are an important component of automated data representation, interoperability, and processing. For the planning of assembly systems, information on the products, processes, and resources as well as their interrelationships are necessary. The most commonly used modeling approach from the digital factory is called Product-Process-Resource model (PPR, see Fig. 1).

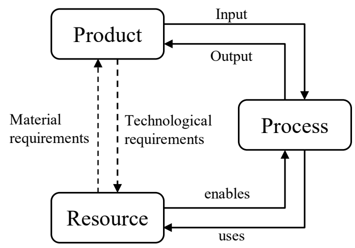

Fig. 1. Product-Process-Resource Model [20]

The product is the result of a transformation process of single part products being transformed by manufacturing processes using a production resource. In order to use a resource for a process, the functional capabilities of the single resource have to be checked under the requirements given by the product.

3. Problem Formulation

This section defines the problem formulation to be solved using the developed method. In addition the underlying assumptions are presented.

3.1. Problem definition

Already selected resources define assembly stations, which must be arranged in a given area. The task is to convert the conceptual layout automatically into a physical one. Under the premise of representing as many planning details as realistically as possible, the tasks are the following:

- Generation of technically reasonable layouts under given boundary conditions.
- Optimization of the assembly stations with regard to their space requirements and utilization.
- Optimization of the positioning of the assembly stations within a given layout on the given shopfloor.

- Definition and arrangement of the conveyor system for connecting the assembly stations.

3.2. Boundary conditions for the intended approach

The approach must cover some boundary conditions, which are briefly presented.

- *Shop-floor boundary*: All resources and assembly stations must be located within the defined shop-floor area.
- *Non-overlapping resource footprints*: In general, the footprints of resources are not allowed to overlap. Exceptions have to be defined explicitly.
- *Investment cost for conveyor setup*: The selection of the conveyor technology must take into account the specified maximum investment costs.
- *Reachability and accessibility*: Resources must be able to reach and interact to all resources with which they are in physical relation. It has to be ensured, that the accessibility is given at any time. This impacts object orientations.

3.3. Assumptions

The following assumptions were made for the planning approach:

- Resources have properties that can be used for their two-dimensional modeling (e.g. description of the footprint as an abstract shape).
- Each assembly station has information on the processes executed at this proper station and relationships to corresponding neighbors. The required Bill-of-Processes (BoP) are available in form of precedence graphs.
- Relations and interactions of single assembly stations are known in advance (e.g. required sequence of appearance).
- Assembly stations are connected via a single conveyor system. This has an influence on the relative positioning and orientation of individual operating resources to each other.

4. Layout planning approach

In this chapter, the developed approach for layout planning of assembly lines is presented. Starting with a rough overview of the two phases of the approach, a detailed description of the individual steps follows.

4.1. Approach overview

Fig. 2 illustrates an overview of the methodical approach. In general, the method is divided into two sequential phases – namely "Workstation Setup" and "Conveyor Setup". In the "Workstation Setup" phase, all resources are modeled as two-dimensional physical objects. Relations are modeled based on physical principles. After the physical system is in an equilibrium state, the phase of "Conveyor Setup" follows. In this phase, conveyor modules connect all related assembly stations, and an optional work-piece-carrier-circulation principle is established.

The available layout is also physically modeled at the beginning of the planning method.

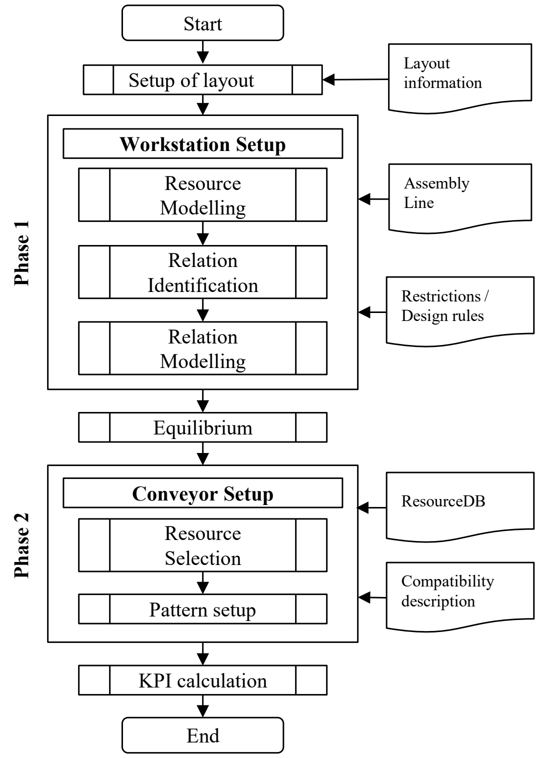

Fig. 2. Overview of the two-staged planning approach

4.2. Physically based modeling

The presented approach is based on the physical principle of minimum potential energy. According to this principle, as described in [16], the total potential energy is defined by internal forces and distances between particles of a physical system. Internal forces (forces of attraction and repulsion) between particles cause motion, converting potential energy of the system into kinetic energy. Consequently, the potential energy of the system will continuously decrease until all objects reach the equilibrium state. In this state the internal forces are balanced, and the particles are in a stable position.

To model attractive and repulsive forces between particles and physical objects, respectively, a modification of the spring-damper system from [18, 19] is used. This will be explained in more detail in chapter 4.4.2.

Fig. 3 shows the concept of physically connected objects (in particular resources of an assembly line), which will be explained step-by-step in the following sections.

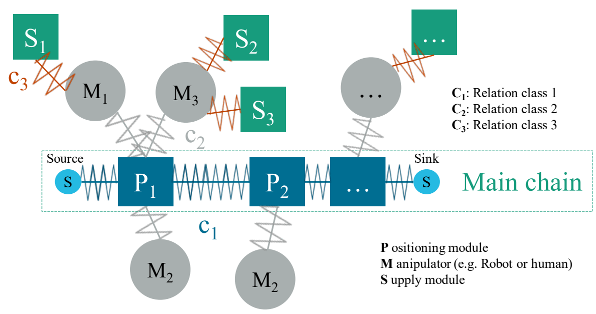

Fig. 3. Concept of physically linked resources of an assembly line

4.3. Setup of the layout on the given shop-floor

The shop-floor area reserved for the arrangement of assembly line resources, is defined by the specification of border points. Each border point is defined with predecessor-successor information to enable shapes that deviate from a simple rectangle (often called "block layout" in literature). Since the resources to be arranged are modeled as physical objects which can change their position, static physical objects must enclose the shopfloor. This ensures that no resource can be placed outside the available area. Other static objects that can be modeled, are interfering contours (e.g. pillars, lifts, chutes), pre-defined entry and exit points of the assembly line or inaccessible (blocked) areas.

4.4. Phase „Workstation Setup"

Within the phase "Workstation Setup", the resources to be arranged, are modeled as physical objects. In this particular phase, the automated identification and modeling of relationships between resources takes place.

4.4.1. Resource modeling

Each assembly station has references to the resources required to perform the individual function. For the transformation of these resources into physical objects, information on their simplified two-dimensional footprint is required. The footprint describes the area requirement of the resource, depending on the specification as an abstract shape element (e.g. circle, rectangle, or polygon). Some resources also have a workspace (e.g. robots or human worker). The workspace is simplified and modeled as a circle wrapping the two-dimensional footprint. Additionally, specific directions can be defined and modeled for resources, such as the direction of work-piece input and output, maintenance, and part supply. These directions are optional and can be used as anchor points at which forces will act.

The approach generally assumes different planning levels for the used resources. Depending on which planning level a resource is assigned to, properties are assigned for the mass and inertia of the physical object of the resource. This mass does not represent the actual mass of the real resource. In a physical system, objects can be displaced due to mass differences ("Newton's law of gravity") and acting forces. Therefore, resources assigned to a higher planning level significantly determines the position of subordinate resources, since they have a higher mass.

Another feature is the assignment of filter classes to individual physical objects. The filter classes enable individual overlapping for specific objects. For this purpose, certain object collisions are excluded from the collision pipeline to be resolved during the physical simulation runs.

4.4.2. Relation identification and modeling

After the resources have been modeled as physical objects, the automated identification of relationships takes place. As shown in Fig. 4, a distinction is made between relationships between resources ($n \times n$ matrix) and between resources and environmental objects ($n \times m$ matrix). A resource cannot have a relation to itself (blacked boxes). But it can have several relations to other resources or environment objects. Therefore, a relationship chart should be seen as a multi-dimensional matrix. Each block represents an information-triple, consisting of two objects which are in relation to each other and the type of relation. The relations can be of various types, even of the same type with different parameters for the same object pair.

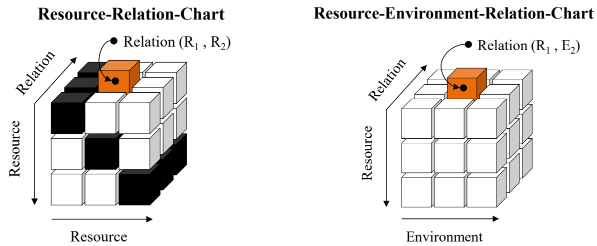

Fig. 4. Multi-dimension relation charts for resource and environment objects

The automated identification of relations is based on the process description within the respective assembly station and their relationships (BoP) to each other (see Fig. 5). Basically, processes of transfer and positioning of work-piece-carriers or products, separation of additional product parts, handling and joining of these, take place within an assembly station.

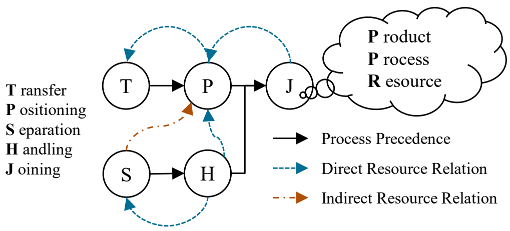

Fig. 5. Basic BoP relation pattern of an assembly workstation

An executing resource is assigned to each process (PPR information). The process types essentially determine which resources are directly or indirectly related to each other. Directly related resources should be positioned as close to each other as possible ("closeness"-relation), since their position significantly influences process times. One example would be to place a handling robot as close as possible to a separation module (which is necessary to separate supplied product parts). Indirect relationships also influence process times, as these affect handling distances. E.g., a separation module arranged close to the work-piece-carrier/product positioning module of a workstation reduces required handling distances. Resources that own an enveloping workspace must be able to reach ("reachability"-relation) and access ("accessibility"-relation) all related resources. This means resources must be located within the workspace with correct orientations. Another relationship would be to constrain the position and orientation of a resource as a function of the position and orientation of another resource or object ("constraining"-relation).

Relationships of resources with the environment would be, for example, the positioning of certain resources in defined areas (e.g. logistic areas) or the connection of the first assembly station of the assembly line with the predefined entry point (product material flow source) and the last workstation with the exit point (product material flow sink), respectively.

After the automated identification of relationships, the physical modeling takes place. The physical concept used in this paper, is the mass-spring-damper model (see Fig. 6), as described in [18, 19].

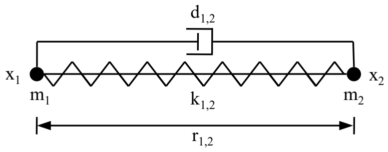

Fig. 6. Mass-Spring-Damper model with two objects

This generally consists of two objects with masses m_1 and m_2, which are interconnected. This connection is described by its spring constant $k_{1,2}$ and its damping constant $d_{1,2}$. The spring exerts forces on the two masses. Those forces are determined by the difference of the rest length $r_{1,2}$ of the spring and its current length ($|x_2 - x_1|$). If objects are connected to each other via spring, then the object with higher mass is decisively responsible for the position of the subordinate object since it determines the direction of the attraction force.

According to the classification of resources to different planning levels, different spring classes result for the definition of the attraction forces. These spring classes influence how fast connected objects are attracted or repulsed. The transient response of a spring connection can also be influenced by the additional definition of a damping factor. This in particular helps determining a state of less relative motion due to energy dissipation.

If no spring connection points (e.g. input and output directions) were defined during the physical modeling of the resource, the geometrical center is initially provided as the "connection point" for all objects on which tensile and compressive forces act. The variation of the rest length $r_{1,2}$ of a spring enables the definition of certain minimum distances between connected objects. If no minimum distances are specified, the system tries to arrange all connected objects as close to each other as possible.

4.5. Equilibrium search process

After all resources have been transformed into physical objects, their initial positioning in the available space of the shopfloor is carried out. Based on the different planning levels, elements of the highest order are successively threaded on an elastic line. All other elements with reference to their superordinate elements are added gradually. The initial arrangement is done randomly within a defined area around the planning element of the highest order of an assembly station.

After the arrangement of the physical objects, defined attractive and repulsive forces are applied simultaneously. Dynamics are derived by using forward numerical simulation over discrete time intervals. Within these time steps forces determine accelerations that cause changes in velocities, which in turn enable translations. This forward extrapolation is called numerical integration.

Since the planning objects are represented in their dimensions within a physics environment, they automatically repel each other (potential field theory). Contact forces occur when objects get into contact. These contact forces are included in a moment equilibrium. Forces are dynamically activated to counteract the current penetration forces. This ensures that there is no overlap between objects. One exception is the contact of objects whose overlapping is allowed by defined filter classes. Due to the action of forces, objects change their initial positions. Objects assigned to a lower planning level can rotate freely around the center of gravity of parent objects as long as no restrictions are defined.

Based on the potential energy between elements and the limiting envelope (border of the available area), the objects arrange themselves in an energetic minimum. The next phase of the planning method starts after all forces have been resolved and the planning objects have no more movements. There, the necessary concatenation by conveyor modules is planned.

4.6. Phase "Conveyor Setup"

In the phase "Conveyor Setup", conveyor patterns are applied to connect all workstations based on their relation to each other. Therefore, partial sections are defined, which depend on the respective positions of resources of the highest order of the assembly stations. For each of these sections, suitable conveyor modules are automatically identified from a conveyor resource database. The selection is performed, based on the transfer characteristic. For example, a differentiation is made between a work-piece-carrier transfer or a direct product transfer. Generally, a match is made between transfer requirements and the capabilities offered by the transfer modules, similar to [3]. The respective modules have defined lengths as well as a certain compatibility to each other. The compatibility is stored in a compatibility database.

From the total quantity of available and technically feasible conveyor modules, compatible ones are defined to form an overall system that covers all required transfer sections. A tree-search masking algorithm that discards incompatible module solutions defines the overall conveyor system. If the assembly line is based on a work-piece-carrier principle, then additional modules are selected to maintain the circulation of these work-piece-carriers in the assembly line. These modules have an influence on the arrangement pattern of the selected conveyor modules.

The evaluation of the transfer system is carried out via fitness function, which is based on a weighted sum. This includes investment costs of the required modules, required space for the conveyor setup, the ratio of achieved conveyor length of the total system to the required length given by the positions of the assembly stations as well as the number of conveyor modules. The latter serves as an indicator for the flexibility in case of adaptation requirements of the assembly line. A defined maximum allowed investment must be maintained. Solutions that exceed this upper limit are rejected.

Modules of the best conveyor system found are then also modeled as physical objects and inserted into the layout. By resolving emerging contact forces with existing objects in the layout, a final fine-tuning of the assembly line solution takes place.

4.7. Key Performance Indicator to rate results

With the presented approach, new layout alternatives for linked assembly systems can be generated with each run due to random start positions of objects. In order to select the best alternative, the definition of a comparative index or fitness function is necessary. Therefore, a weighted sum is applied. This takes into account key performance indicators such as the space required for the assembly line or the investment costs of the conveyor system required for it.

5. Evaluation

In the now presented example application, the conceptual layout of the assembly line consists of nine assembly stations. They should be arranged sequentially in a straight line, defined by a given entry and exit point, respectively.

Three planning levels are defined, to each of which resources are assigned. The first level contains work-piece-carrier positioning modules and a dedicated machine, which is treated as an already complete assembly station. An assembly station has only one positioning module, which influences the position of further operating equipment of the station. The second level contains resources, which are required for handling and joining tasks. In the present case, these are human workers, who have a workspace defined by their reach. Separation modules are assigned to the lowest planning level. These are directly related to the handling resources and must be located within their working spaces.

One planning premise is, that automated resources should be spatially separated from manual ones. Separation modules are therefore restricted to the back-side and human workers to the front-side of the assembly line. This is achieved through a “constraining“-relation, which utilizes the positioning module of a workstation as reference object.

As described in section 4.5, the resources of the highest planning level are arranged sequentially based on the given workstation sequence. Other resources of a workstation are added after the workstation resource of the highest planning level is placed. Fig. 7 shows a generated result after the system found its equilibrium state.

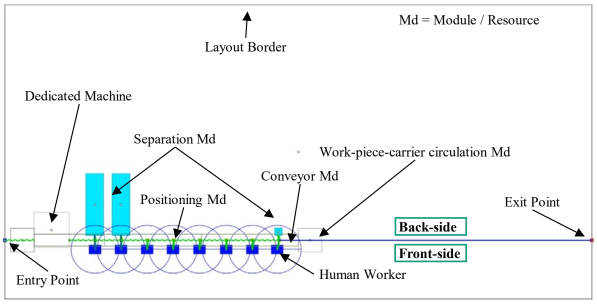

Fig. 7. Evaluation with example assembly line

6. Conclusion and Future Prospect

In this paper, a methodical approach for integrated resource spatial arrangement and material flow linking is presented to automatically convert conceptual layouts of assembly lines into physical drafts. The approach uses physical principles to represent resources and their relationships to each other. Resources and relationships are assigned to planning levels that differ in certain modeling parameters.

Critically, the presented approach is able to generate an equilibrium state for the planning objects. This equilibrium state fulfills all boundary conditions set. Unfortunately, this minimum state might represent a local minimum solution. In order to find optimal layouts, a stimulation of the system should take place to generate further solutions. The following approaches would be conceivable:

- Temporary deactivation of rejection reactions
- Combinatorial rearrangement of objects
- Variation of parameterizations (resources and relationship modeling) within certain limits
- Semi-automatic planning with human interaction

Furthermore, deeper investigations are necessary to compare the performance and result quality of this novel approach to other approaches for automated layout planning as described in section 2.1.

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